09:18:25 OCA PAD AMENDMENT - PROJECT HEADER INFORMATION 06/18/92

Active

Project #: E-24-651 Cost share #: E-24-360 Rev #: 12
Center # : R6519-0A0 Center shr #: F6519-0A0 OCA file #:
Work type : RES
Contract#: DDM-8719128 Mod #: ADM REV Document : GRANT
Prime #: Contract entity: GTRC

Subprojects ? : N CFDA: 47.041
Main project #: PE #: N/A

Project unit: ISYE Unit code: 02.010.124
Project director(s):
NEMHAUSER G L ISYE (404)894-2306
JOHNSON E L ISYE (404)-

Sponsor/division names: NATL SCIENCE FOUNDATION / GENERAL
Sponsor/division codes: 107 / 000

Award period: 880601 to 921130 (performance) 930228 (reports)

| Sponsor amount | New this change | Total to date |
|---|---|---|
| Contract value | 0.00 | 533,109.00 |
| Funded | 0.00 | 533,109.00 |
| Cost sharing amount | | 17,698.00 |

Does subcontracting plan apply ?: N

Title: RESEARCH IN MIXED-INTGER PROGRAMMING

PROJECT ADMINISTRATION DATA

OCA contact: Mildred S. Heyser 894-4820

Sponsor technical contact

DONALD GROSS
(202)357-5167

NATIONAL SCIENCE FOUNDATION
ENG/ECS
WASHINGTON, D.C. 20550

Sponsor issuing office

ROSA C. PATTERSON
(202)357-9602

NATIONAL SCIENCE FOUNDATION
1800 G STREET, N.W.
ENG/ECS
WASHINGTON, D.C> 20550

Security class (U,C,S,TS) : U ONR resident rep. is ACO (Y/N): N
Defense priority rating : N/A NSF supplemental sheet
Equipment title vests with: Sponsor GIT X
IBM PS/2 MODEL 80
Administrative comments -
TO CORRECT NAME OF CO-P.I.

GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 12/10/92

Project No. E-24-651 Center No. R6519-0A0

Project Director NEMHAUSER G L School/Lab ISYE

Sponsor NATL SCIENCE FOUNDATION/GENERAL

Contract/Grant No. DDM-8719128 Contract Entity GTRC

Prime Contract No.

Title RESEARCH IN MIXED-INTGER PROGRAMMING

Effective Completion Date 921130 (Performance) 930228 (Reports)

| Closeout Actions Required: | Y/N | Date Submitted |
|---|---|---|
| Final Invoice or Copy of Final Invoice | Y | |
| Final Report of Inventions and/or Subcontracts | Y | |
| Government Property Inventory & Related Certificate | N | |
| Classified Material Certificate | Y | |
| Release and Assignment | N | |
| Other | N | |

Comments EFFECTIVE DATE 6-1-88. CONTRACT VALUE $533,109.

Subproject Under Main Project No.

Continues Project No.

Distribution Required:

| | |
|---|---|
| Project Director | Y |
| Administrative Network Representative | Y |
| GTRI Accounting/Grants and Contracts | Y |
| Procurement/Supply Services | Y |
| Research Property Managment | Y |
| Research Security Services | N |
| Reports Coordinator (OCA) | Y |
| GTRC | Y |
| Project File | Y |
| Other HARRY VANN-FMD | Y |
| FRED CAIN-OOD | Y |

NOTE: Final Patent Questionnaire sent to PDPI.

PROGRESS REPORT

NSF Grant No. ECS-8719128

Title: Research in Mixed-Integer Programming

Principal Investigators: Ellis L. Johnson, Coca-Cola Professor
George L. Nemhauser, Chandler Professor
School of Industrial and Systems Eng.
Georgia Institute of Technology

Period: 6/1/88 - 5/31/89 - first year of a three-year continuing grant.

## I. Scientific Progress

### I.1 Work Completed

The following studies were started under NSF Grant ECS-8307473 and completed during the past year. Ph.D. dissertation abstracts describing the results are attached and research papers are being prepared.

A. A Constraint Generation Algorithm for Node Packing (Gabriele Sigismondi)
B. An Integer Programming Approach to Edge Coloring (Sungsoo Park)
C. Parallel Algorithms for the Set Covering Problem (Russell Rushmeier)

The results of each of these studies will be used in the current project. Sigismondi's clique and odd hole generation techniques can be generalized and applied to mixed-integer programs. Park has provided an integer programming algorithm that combines constraint and column generation and Rushmeier has used parallel processing in decomposition and branch-and-bound.

### I.2 Work in Progress

#### A. Prototype Algorithm for Mixed Integer Programming

We are in the process of designing and coding a modular experimental program to solve mixed integer programming problems. The code will ultimately include features such as automatic efficient formulation, logical testing, decomposition, constraint and column generation, flexible branching, and parallel processing.

#### B. Prototype Problems for Mixed Integer Programming

We have selected two prototype problems to provide test examples of large mixed-integer models on which our ideas and examples can be evaluated. One is a clustering problem which can

be imagined as partitioning the metropolitan areas of the U.S. into a new set of 48 states with the property that the sum of the overall distances between the inhabitants within each state is minimized. This generic clustering problem has numerous applications in circuit design, location, distribution and manufacturing, and information systems. The other is the Steiner branching problem which is a multicommodity flow model with applications to circuit and other network design problems. Both of these problems have several formulations involving tradeoffs between a large number of variables versus a large number of constraints and ample opportunities for constraint and column generation, decomposition and parallel processing.

C. Forbidden Minor Characterizations in Graphs and Their Algorithmic Implications

The prototype example for this work is the well-known result characterizing graphs having no complete subgraph on four nodes as a minor as having a series or parallel reduction. Algorithmic implications are so numerous that almost every problem is easier on graphs without these minors. The focus of the current investigation is to push the results further in order to fill the void in such results between series-parallel and planar graphs as well as to obtain results for non-planar graphs.

## II. Publications

1. S. Chopra and E.L. Johnson, "Octahedron Free and Cube Free Graphs," January, 1989 (submitted to Journal of Graph Theory)

2. G.L. Nemhauser and S. Park, "A Polyhedral Approach to Edge Coloring," Industrial and Systems Engineering Report No. J-89-01, Georgia Institute of Technology, March 1989 (submitted to Mathematical Programming).

3. G.L. Nemhauser and L. A. Wolsey, "Integer Programming," Industrial and Systems Engineering Report No. J-88-17, Georgia Institute of Technology, July 1988 (to appear in Handbooks in Operations Research and Management Science, Vol. 1, Optimization, G.L. Nemhauser, A.H.G. Rinnooy Kan and M.J. Todd, eds., North-Holland.

## III. Presentations

1. E.L. Johnson, "Recent Advances in Preprocessing Techniques for Large Mixed-Integer Programming Problems," The 13th

International Symposium on Mathematical Programming, Tokyo, August 1988, and ORSA/TIMS Joint National Meeting, Denver, October 1988 (with T. Ciriani and S. Gliozzi).

2. G.L. Nemhauser, "A Strong Cutting Plane Algorithm for the Node Packing Problem," The 13th International Symposium on Mathematical Programming, Tokyo, August 1988 (with G. Sigismondi).

3. G.L. Nemhauser, "Integer Programming Approach to the Edge Coloring Problem," ORSA/TIMS Joint National Meeting, Denver, October 1988 and Southeastern Meeting on Graph Theory and Combinatorics, Boca Raton, February, 1989 (with S. Park).

4. R.A. Rushmeier, "A Comparison of Parallel Methods for the Set Covering Problem," ORSA/TIMS/CORS Joint National Meeting, Vancouver, May 1989 (with G.L. Nemhauser).

## IV. Current Personnel

Principal Investigators: Ellis A. Johnson and George L. Nemhauser

Research Associate: Gabriele C. Sigismondi
Ph.D Students: Heesang Lee, Anuj Mehrotra, Pier Sigismondi, Pamela Vance*
* funded by other sources

Visiting Scholar: Laurence Wolsey

## V. Budget

It is anticipated that the first year's budget will be fully spent by 5/31/89. A request for $158,544 for the second year is detailed on the following budget page.

FUNDS OMITTED FROM FIRST YEAR
June 1, 1988 - May 31, 1989

# SUMMARY PROPOSAL BUDGET

OMB No. 3145-0058
Exp. Date 12/31/85

FOR NSF USE ONLY

ANIZATION
**EORGIA TECH RESEARCH CORPORATION**

PROPOSAL NO. | DURATION (MONTHS) Proposed | Granted

NCIPAL INVESTIGATOR/PROJECT DIRECTOR
George L. Nemhauser

AWARD NO.

| ENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets) | NSF FUNDED PERSON-MOS. CAL. | ACAD | SUMR | FUNDS REQUESTED BY PROPOSER | FUNDS GRANTED BY NSF (IF DIFFERENT) |
|---|---|---|---|---|---|
| | | | | $ | $ |
| | | | | | |
| | | | | | |
| | | | | | |
| ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE) | | | | | |
| ( ) TOTAL SENIOR PERSONNEL (1-5) | | | | | |
| OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS) | | | | | |
| ( ) POST DOCTORAL ASSOCIATES | | | | | |
| ( ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.) | | | | | |
| ( ) GRADUATE STUDENTS | | | | | |
| ( ) UNDERGRADUATE STUDENTS | | | | | |
| ( ) SECRETARIAL-CLERICAL | | | | | |
| ( ) OTHER | | | | | |
| TOTAL SALARIES AND WAGES (A+B) | | | | | |
| FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) | | | | | |
| TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C) | | | | | |
| D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $1,000.) | | | | | |
| TOTAL PERMANENT EQUIPMENT | | | | | |
| E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS) | | | | | |
| 2. FOREIGN | | | | | |
| F. PARTICIPANT SUPPORT COSTS | | | | | |
| 1. STIPENDS $ | | | | | |
| 2. TRAVEL | | | | | |
| 3. SUBSISTENCE | | | | | |
| 4. OTHER | | | | | |
| TOTAL PARTICIPANT COSTS | | | | | |
| G. OTHER DIRECT COSTS | | | | | |
| 1. MATERIALS AND SUPPLIES | | | | | |
| 2. PUBLICATION COSTS/PAGE CHARGES | | | | | |
| 3. CONSULTANT SERVICES | | | | | |
| 4. COMPUTER (ADPE) SERVICES | | | | | |
| 5. SUBCONTRACTS | | | | | |
| 6. OTHER | | | | | |
| TOTAL OTHER DIRECT COSTS | | | | | |
| H. TOTAL DIRECT COSTS (A THROUGH G) | | | | | |
| I. INDIRECT COSTS (SPECIFY) The approved rate for indirect costs is 60%. We were allowed only 52.8% with the first year funding. | | | | | |
| TOTAL INDIRECT COSTS Amount omitted . . . . | | | | 6,383 | |
| J. TOTAL DIRECT AND INDIRECT COSTS (H + I) | | | | 6,383 | |
| K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS GPM 252 AND 253) | | | | | |
| L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K) | | | | $ 6,383 | $ |

PI/PD TYPED NAME & SIGNATURE* George Nemhauser — DATE 9/3/87

INST. REP. TYPED NAME & SIGNATURE* — DATE

FOR NSF USE ONLY
INDIRECT COST RATE VERIFICATION
Date Checked | Date of Rate Sheet | Initials - DGC Program

NSF Form 1030 (4-83) *Supersedes All Previous Editions*

*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPM 233)

COND YEAR BUDGET
ne 1, 1989 - May 31, 1990

# SUMMARY PROPOSAL BUDGET

OMB No. 3145-0058
Exp. Date 12/31/85

FOR NSF USE ONLY

ANIZATION
**EORGIA TECH RESEARCH CORPORATION**

PROPOSAL NO. | DURATION (MONTHS) Proposed | Granted

ICIPAL INVESTIGATOR/PROJECT DIRECTOR
orge L. Nemhauser

AWARD NO.

| ENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets) | NSF FUNDED PERSON-MOS. CAL. | ACAD | SUMR | FUNDS REQUESTED BY PROPOSER | FUNDS GRANTED BY NSF (IF DIFFERENT) |
|---|---|---|---|---|---|
| George Nemhauser, Co-PI | 2 | | | $ 20,152 | $ |
| Ellis Johnson, Co-PI | 1 | | | 8,726 | |
| | | | | | |
| | | | | | |
| ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE) | | | | | |
| ( 2) TOTAL SENIOR PERSONNEL (1-5) | 3 | | | 28,878 | |
| OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS) | | | | | |
| (1 ) POST DOCTORAL ASSOCIATES | 2 | | | 8,812 | |
| (1 ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.) Res.Assoc. | 6 | | | 19,803 | |
| (2 ) GRADUATE STUDENTS @ 2448/Qtr. 1/3 T (4 Qtrs.) | | | | 19,584 | |
| ( ) UNDERGRADUATE STUDENTS | | | | | |
| ( ) SECRETARIAL-CLERICAL | | | | | |
| ( ) OTHER | | | | | |
| TOTAL SALARIES AND WAGES (A+B) | | | | 77,077 | |
| FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) @ 25.5% of A.6, B.1, B.2 | | | | 14,661 | |
| TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C) | | | | 91,738 | |
| . PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $1,000:) | | | | | |
| TOTAL PERMANENT EQUIPMENT | | | | | |
| E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS) | | | | 3,000 | |
| 2. FOREIGN | | | | | |
| F. PARTICIPANT SUPPORT COSTS | | | | | |
| 1. STIPENDS $ | | | | | |
| 2. TRAVEL | | | | | |
| 3. SUBSISTENCE | | | | | |
| 4. OTHER | | | | | |
| TOTAL PARTICIPANT COSTS | | | | | |
| G. OTHER DIRECT COSTS | | | | | |
| 1. MATERIALS AND SUPPLIES | | | | 4,352 | |
| 2. PUBLICATION COSTS/PAGE CHARGES | | | | | |
| 3. CONSULTANT SERVICES | | | | | |
| 4. COMPUTER (ADPE) SERVICES CPU time on Cyber 205 at Univ of GA (No chg) | | | | | |
| 5. SUBCONTRACTS (to NSF) | | | | | |
| 6. OTHER | | | | | |
| TOTAL OTHER DIRECT COSTS | | | | 4,352 | |
| H. TOTAL DIRECT COSTS (A THROUGH G) | | | | 99,090 | |
| I. INDIRECT COSTS (SPECIFY) @ 60% of direct Cost-Shared in accordance to NSF policy | | | | | |
| TOTAL INDIRECT COSTS | | | | 59,454 | |
| J. TOTAL DIRECT AND INDIRECT COSTS (H + I) | | | | 158,544 | |
| K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS GPM 252 AND 253) | | | | | |
| L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K) | | | | $ 158,544 | $ |

PI/PD TYPED NAME & SIGNATURE*
George Nemhauser
DATE 4/3/89

INST. REP. TYPED NAME & SIGNATURE*
DATE

FOR NSF USE ONLY
INDIRECT COST RATE VERIFICATION
Date Checked | Date of Rate Sheet | Initials - DGC Program

NSF Form 1030 (4-83) *Supersedes All Previous Editions*

*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPM 233)

SUMMARY BUDGET
June 1, 1988 - May 31, 1990

OMB No. 3145-0058
Exp. Date 12/31/85

# SUMMARY PROPOSAL BUDGET

FOR NSF USE ONLY

ZATION
RGIA TECH RESEARCH CORPORATION

PROPOSAL NO. | DURATION (MONTHS) Proposed | Granted

AL INVESTIGATOR/PROJECT DIRECTOR
ge L. Nemhauser

AWARD NO.

| OR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (each separately with title; A.6. show number in brackets) | NSF FUNDED PERSON-MOS. CAL. | ACAD | SUMR | FUNDS REQUESTED BY PROPOSER | FUNDS GRANTED BY NSF (IF DIFFERENT) |
|---|---|---|---|---|---|
| orge Nemhauser, Co-PI | 2 | | | $ 20,152 | $ |
| Lis Johnson, Co-PI | 1 | | | 8,726 | |
| | | | | | |
| | | | | | |
| ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE) | | | | | |
| ( 2) TOTAL SENIOR PERSONNEL (1-5) | 3 | | | 28,878 | |
| ER PERSONNEL (SHOW NUMBERS IN BRACKETS) | | | | | |
| ) POST DOCTORAL ASSOCIATES | 2 | | | 8,812 | |
| ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.) Res.Assoc. | 6 | | | 19,803 | |
| ) GRADUATE STUDENTS @ 2448/Qtr. 1/3 T (4 Qtrs.) | | | | 19,584 | |
| ) UNDERGRADUATE STUDENTS | | | | | |
| ) SECRETARIAL-CLERICAL | | | | | |
| ) OTHER | | | | | |
| TAL SALARIES AND WAGES (A+B) | | | | 77,077 | |
| NGE BENEFITS (IF CHARGED AS DIRECT COSTS) @ 25.5% of A.6, B.1, B.2 | | | | 14,661 | |
| TAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C) | | | | 91,738 | |
| MANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $1,000.) | | | | | |
| OTAL PERMANENT EQUIPMENT | | | | | |
| AVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS) | | | | 3,000 | |
| 2. FOREIGN | | | | | |
| RTICIPANT SUPPORT COSTS | | | | | |
| STIPENDS $ | | | | | |
| TRAVEL | | | | | |
| SUBSISTENCE | | | | | |
| OTHER | | | | | |
| TOTAL PARTICIPANT COSTS | | | | | |
| THER DIRECT COSTS | | | | | |
| MATERIALS AND SUPPLIES | | | | 4,352 | |
| PUBLICATION COSTS/PAGE CHARGES | | | | | |
| CONSULTANT SERVICES | | | | | |
| COMPUTER (ADPE) SERVICES CPU time on Cyber 205 at Univ of GA (No chg) | | | | | |
| SUBCONTRACTS (to NSF) | | | | | |
| OTHER | | | | | |
| TOTAL OTHER DIRECT COSTS | | | | 4,352 | |
| OTAL DIRECT COSTS (A THROUGH G) | | | | 99,090 | |
| NDIRECT COSTS (SPECIFY) @ 60% of direct, plus amount omitted from first year. | | | | | |
| OTAL INDIRECT COSTS Cost-shared in accordance w/ NSF policy | | | | 65,837 | |
| TOTAL DIRECT AND INDIRECT COSTS (H + I) | | | | 164,927 | |
| RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS GPM 252 AND 253) | | | | | |
| AMOUNT OF THIS REQUEST (J) OR (J MINUS K) | | | | $ 164,927 | $ |

| O TYPED NAME & SIGNATURE* | DATE | FOR NSF USE ONLY |
|---|---|---|
| eorge Nemhauser | 9/3/87 | INDIRECT COST RATE VERIFICATION |
| T REP TYPED NAME & SIGNATURE* | DATE | Date Checked / Date of Rate Sheet / Initials OGC / Program |

*SIGNATURES REQUIRED ONLY FOR REVISED

E-24-651

GEORGIA TECH 1885-1985

DESIGNING TOMORROW TODAY

**Georgia Institute of Technology**
School of Industrial and Systems Engineering
Atlanta, Georgia 30332-0205
(404) 894-2300 /894-2306
GNEMHAUS@GTRI01.bitnet

March 30, 1990

Dr. Donald Gross
Program Director, Operations Research
National Science Foundation
1800 G Street, N.W., Rm.1128
Washington, D.C. 20550

Dear Don:

For NSF Grant No. DDM-8719128, enclosed is the abstract and progress report for the second year and proposed budget for the third year.

I am a very excited about GT-MIO as a research tool for a large community of people. It is generally said that a problem with selling OR research is the lack of tangible products. I think we have one here that can be of tremendous benefit to other researchers who experiment with different approaches of solving large-scale MIP's.

The final year of the project will be especially interesting as we get more involved in trying to solve different classes of problems.

Sincerely,

George L. Nemhauser
Chandler Professor

GLN/yk

Enclosure

VISED THIRD YEAR BUDGET

OMB No. 3145-0058
Exp. Date 12/31/85

# SUMMARY PROPOSAL BUDGET

| FOR NSF USE ONLY | | |
|---|---|---|
| PROPOSAL NO. | DURATION (MONTHS) Proposed | Granted |
| AWARD NO. | | |

ORGANIZATION
**GEORGIA TECH RESEARCH CORPORATION**

PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR
George L. Nemhauser

| A. SENIOR PERSONNEL: PI/PD, Co-PI's, Faculty and Other Senior Associates (List each separately with title; A.6. show number in brackets) | NSF FUNDED PERSON-MOS. CAL. | ACAD | SUMR | FUNDS REQUESTED BY PROPOSER | FUNDS GRANTED BY NSF (IF DIFFERENT) |
|---|---|---|---|---|---|
| George L. Nemhauser, Co-PI | 2 | | | $ 15,833 | $ |
| Ellis Johnson, Co-PI | 2 | | | 15,833 | |
| | | | | | |
| | | | | | |
| ( ) OTHERS (LIST INDIVIDUALLY ON BUDGET EXPLANATION PAGE) | | | | | |
| ( 2 ) TOTAL SENIOR PERSONNEL (1-5) | 4 | | | 31,666 | |
| B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS) | | | | | |
| ( 1 ) POST DOCTORAL ASSOCIATES | 1 | | | 4,665 | |
| ( 1 ) OTHER PROFESSIONALS (TECHNICIAN, PROGRAMMER, ETC.) Res.Assoc. | 6 | | | 20,830 | |
| ( 3 ) GRADUATE STUDENTS @ 2448/Qtr 1/3 T 4 Qtrs ea. | | | | 29,376 | |
| ( ) UNDERGRADUATE STUDENTS | | | | | |
| ( 1 ) SECRETARIAL-CLERICAL | | | | 1,499 | |
| ( ) OTHER | | | | | |
| TOTAL SALARIES AND WAGES (A+B) | | | | 88,036 | |
| C. FRINGE BENEFITS (IF CHARGED AS DIRECT COSTS) @ 26.3% of A.6, B.1, B.2, B.5 | | | | 15,428 | |
| TOTAL SALARIES, WAGES AND FRINGE BENEFITS (A+B+C) | | | | 103,464 | |
| D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $1,000.) | | | | | |
| TOTAL PERMANENT EQUIPMENT | | | | | |
| E. TRAVEL 1. DOMESTIC (INCL. CANADA AND U.S. POSSESSIONS) | | | | 3,000 | |
| 2. FOREIGN | | | | | |
| F. PARTICIPANT SUPPORT COSTS | | | | | |
| 1. STIPENDS $ | | | | | |
| 2. TRAVEL | | | | | |
| 3. SUBSISTENCE | | | | | |
| 4. OTHER | | | | | |
| TOTAL PARTICIPANT COSTS | | | | | |
| G. OTHER DIRECT COSTS | | | | | |
| 1. MATERIALS AND SUPPLIES | | | | 2,874 | |
| 2. PUBLICATION COSTS/PAGE CHARGES | | | | | |
| 3. CONSULTANT SERVICES | | | | | |
| 4. COMPUTER (ADPE) SERVICES | | | | | |
| 5. SUBCONTRACTS | | | | | |
| 6. OTHER | | | | | |
| TOTAL OTHER DIRECT COSTS | | | | 2,874 | |
| H. TOTAL DIRECT COSTS (A THROUGH G) | | | | 109,338 | |
| I. INDIRECT COSTS (SPECIFY) @ 62.5% of direct | | | | | |
| TOTAL INDIRECT COSTS | | | | 68,337 | |
| J. TOTAL DIRECT AND INDIRECT COSTS (H + I) | | | | 177,675 | |
| K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS GPM 252 AND 253) | | | | | |
| L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K) | | | | $177,675 | $ |

| PI/PD TYPED NAME & SIGNATURE* | DATE | FOR NSF USE ONLY |
|---|---|---|
| | 3/30/80 | INDIRECT COST RATE VERIFICATION |
| INST. REP. TYPED NAME & SIGNATURE* | DATE | Date Checked / Date of Rate Sheet / Initials DGC / Program |

NSF Form 1030 (4-83) *Supersedes All Previous Editions*

*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET (GPM 233)

WILL BE COST SHARED IN ACCORDANCE TO NSF POLICY

NSF Grant No. DDM-8719128

Title: Research in Mixed Integer Programming

Principal Investigators: Ellis L. Johnson, Coca-Cola Professor
George L. Nemhauser, Chandler Professor
School of Industrial and Systems Eng.
Georgia Institute of Technology

Period: 6/1/89 - 5/31/90 - Second year of a three-year Grant

## Abstract

We have completed the initial implementation of a modular experimental software system for solving mixed-integer programming (MIP) problems. The system is called GT-MIO (Georgia Tech Mixed-Integer Optimizer).

The heart of GT-MIO is a linear programming based branch-and-bound algorithm. It is implemented on top of the CPLEX callable library, a software library that provides capabilities to solve and modify linear programs and interpret their solutions.

The design of GT-MIO is based on the philosophy that to solve MIPs efficiently one needs to take advantage of the problem structure. Therefore, GT-MIO provides entry points that allow an application program to enter problem specific knowledge. This knowledge can be used to generate primal solutions, strong cutting planes and special branching rules. Other features, such as the possibility of generating additional variables as in a decomposition algorithm, are still being implemented.

We believe that GT-MIO will be widely used by researchers working in both methodology and applications of MIP, including production, distribution and scheduling. GT-MIO enables the user to experiment with different formulations and strategies for solving their applications. Since the formulation/strategy set is rich and the interactions between the options are complex, GT-MIO becomes a tool for doing further research. In addition, there is the option of using GT-MIO in its default mode as a general purpose MIP solver.

PROGRESS REPORT

NSF Grant No. DDM-8719128

Title: Research in Mixed Integer Programming

Principal Investigators: Ellis L. Johnson, Coca-Cola Professor
George L. Nemhauser, Chandler Professor
School of Industrial and Systems Eng.
Georgia Institute of Technology

Period: 6/1/89 - 5/31/90 - Second year of a three-year grant

## I. Work in Progress

### A. GT-MIO: A Prototype Algorithm for Mixed-Integer Programming

We have completed the initial implementation of a modular experimental software system for solving mixed-integer programming (MIP) problems. The system is called GT-MIO (Georgia Tech Mixed-Integer Optimizer). Documentation is being prepared and we expect to release the code throughout the research community in about three months.

The heart of GT-MIO is a linear programming based branch-and-bound algorithm. It is implemented on top of the CPLEX callable library, a software library that provides capabilities to solve and modify linear programs and interpret their solutions.

The design of GT-MIO is based on the philosophy that to solve MIPs efficiently one needs to take advantage of the problem structure. Therefore, GT-MIO provides entry points that allow an application program to enter problem specific knowledge. This knowledge can be used to generate primal solutions, strong cutting planes and special branching rules. Other features, such as the possibility of generating additional variables as in a decomposition algorithm, are still being implemented.

We have selected several classes of prototype problems for which we are building the application programs. These include node packing (for the purpose of studying a purely combinatorial problem), job shop scheduling (for testing different formulations and cutting plane procedures), submodular function maximization (for using mixed-integer programming to provide a unified model for a broad class of combinatorial problems), and multicommodity flows, clustering and set partitioning (for testing ideas of column generation in solving large-scale MIPs).

We believe that GT-MIO will be widely used by researchers working in both methodology and applications of MIP, including production, distribution and scheduling. GT-MIO enables the user to experiment with different formulations and strategies for solving their applications. Since the formulation/strategy set is rich and the interactions among the options are complex, GT-MIO becomes a tool for doing further research. In addition, there is the option of using GT-MIO in its default mode as a general purpose MIP solver.

B. Graphs and Polyhedral Combinatorics

Theoretical investigations on some related problems in graphs and combinatorics are also in progress. These include Johnson's work with Sunil Chopra and Neil Robertson on the characterization of flat graphs and Johnson's work with Zhang Zhou on a subadditive facet description for mixed integer programming based on a master problem with infinitely many columns.

## II. Publications

1. R. Aboudi and G.L. Nemhauser, "Some Facets for an Assignment problem with Side Constraints," to appear in Operations Research.

2. R. Aboudi and G.L. Nemhauser, "An Assignment Problem with Side Constraints: Strong Cutting Planes and Separation," to appear in Economic Decision Making: Games, Econometrics and Optimization, J. Gabszewicz, J.F. Richard and L.A. Wolsey (eds.), North-Holland, 1990.

3. S. Chopra, D.L. Jensen and E.L. Johnson, "Polyhedra of Regular p-nary Group Problems," Mathematical Programming, 43, 1-29, 1989.

4. G. Cornuejols, G.L. Nemhauser and L.A. Wolsey, "The Uncapacitated Facility Location Problem," to appear in Discrete Location Theory, R.L. Francis and P. Mirchandini, (eds.), Wiley, 1990.

5. H. Gan and E.L. Johnson, "Four Problems on Graphs with Excluded Minors," Mathematical Programming, 45, 311-330, 1989.

6. E.L. Johnson, "On Binary Group Problems Having the Fulkerson Property," in Combinatorial Optimization, B. Simeone (ed.), Springer-Verlag, 57-112, 1989.

7. G.L. Nemhauser and G. Sigismondi, "A Strong Cutting Plane/ Branch-and-Bound Algorithm for Node Packing," ISyE Report No. J-89-03 (submitted for publication).

8. G.L. Nemhauser, G. Sigismondi, and P. Vance, "A Characterization of the Coefficients in Facet-Defining Lifted Cover Inequalities," ISyE Report No. J-89-06 (submitted for publication).

9. R. Rushmeier and G.L. Nemhauser, "Performance of Parallel Branch-and-Bound Algorithms for the Set Covering Problem," ISyE Report No. J-89-02 (submitted for publication).

10. R. Rushmeier and G.L. Nemhauser, "Performance of a Parallel Cost Splitting Algorithm for the Set Covering Problem," ISyE Report No. J-90-03 (submitted for publication).

11. M. Savelsbergh, "A Cutting Plane Algorithm for the Single Machine Scheduling Problem with Release Times," (in preparation).

12. G. Sigismondi, M.W. Savelsbergh and G.L. Nemhauser, "Georgia Tech Mixed Integer Optimizer - GT-MIO," (in preparation).

## III. Presentations

The principal investigators have presented their work on mixed-integer programming at the following conferences and seminars.

Conferences: DIMACS Meeting on Combinatorial Optimization (Morristown, June, 1989); IBM Europe Summer School on Mathematical Programming Systems (Partenkirchen, West Germany, July, 1989); ORSA/TIMS National Meeting (New York, October, 1989); Oberwolfach Meeting on Mathematical Programming (Oberwolfach, West Germany, January, 1990); Southeastern Meeting on Graph Theory and Combinatorics (Boca Raton, February, 1990), ORSA/TIMS National Meeting (Las Vegas, May, 1990).

University seminars: Yale (June, 1989); Clemson (September, 1989), Northwestern (March, 1990); Waterloo (May, 1990).

## IV. Personnel

Principal Investigators: Ellis A. Johnson, George L. Nemhauser
Research Associate: Gabriele C. Sigismondi
Ph.D Students: Heesang Lee, Anuj Mehrotra, Pamela Vance*, Eric Wikum*

PROGRESS REPORT
NSF Grant No. DDM-8719128
Period: 6/1/89 - 5/31/90

Visiting Scholars: Martin Savelsbergh*, Eindhoven University
Laurence Wolsey*, University of Louvain
*funded by other sources.

V. Budget

It is anticipated that the second year's budget will be fully spent by 5/31/90. A request for $177,675 for the third year is detailed on the enclosed budget page.

**NSF Grant No. DDM-8719128**

**Amount:** $ 483,109

**Period:** 6/1/88 - 11/30/91

**Title:** Research in Mixed Integer Programming

**Principal Investigators:** Ellis L. Johnson, Coca-Cola Professor
George L. Nemhauser, Chandler Professor
School of Industrial and Systems Eng.
Georgia Institute of Technology

## I. Summary of Completed Work

### A. MINTO: Mixed-Integer Optimizer [12]

We have completed the initial implementation of MINTO, which is a modular experimental software system for solving mixed-integer programming (MIP) problems. Documentation is being prepared and we expect to release the code throughout the research community in about three months.

The heart of MINTO is a linear programming based branch-and-bound algorithm. It is implemented on top of the CPLEX callable library, a software library that provides capabilities to solve and modify linear programs and interpret their solutions. The design of MINTO is based on the philosophy that to solve MIPs efficiently one needs to take advantage of the problem structure. Therefore, MINTO provides entry points that allow an application program to enter problem specific knowledge. This knowledge can be used to

generate primal solutions, strong cutting planes and special branching rules. Other features, such as the possibility of generating additional variables, as in a decomposition algorithm, are still being implemented. See Sections 2 and 3 of the Project Description for a more detailed description of MINTO and plans for further developments.

We have developed application programs for some generic problems. These include node packing (for the purpose of developing strong preprocessing for MINTO), job shop scheduling (for testing different formulations and cutting plane procedures), submodular function maximization (for using mixed-integer programming to provide a unified model for a broad class of combinatorial problems) and clustering (for testing ideas of column generation in solving large-scale MIPs).

We believe that MINTO will be widely used by researchers working in both methodology and applications of MIP, including production, distribution and scheduling. MINTO enables the user to experiment with different formulations and strategies for solving their applications. Since the formulation/strategy set is rich and the interactions among the options are complex, MINTO becomes a tool for doing further research. In addition, there is the option of using MINTO in its default mode as a general purpose MIP solver.

**B. Polyhedral Combinatorics: Valid Inequalities and Separation**

We have studied several combinatorial optimization problems from the polyhedral point of view. We have constructed classes of

inequalities that contain the convex hull of feasible solutions, developed algorithms for finding violated inequalities and algorithms for strengthening the violated inequalities. Work of this type appears in:

[1,2] for a constrained assignment problem that was used to model a problem in allocating classrooms;

[9] for maximizing submodular functions, a very general problem that includes max cut, facility location and node packing as special cases;

[10] for edge coloring of graphs (covering edges by matchings), a problem that was used to study column generation in integer programming;

[11] for 1-machine job shop scheduling, an apparently very difficult problem for the polyhedral approach with an excellent opportunity to test cut generation procedures;

[13] for node packing; especially a method for maximum lifting of odd-hole inequalities;

[14] for 0-1 programming; characterization of lifting coefficients for cover inequalities.

**C. Polyhedral Results in Integer Programming**

The group problem of integer programming provides a theoretical base for classifying and studying problems. One special case of great interest is the binary group problem. In [7], we relate Gomory's lifting of facets for group problems to Fulkerson's blocking polyhedra and minors of binary matroids. The notion of

forbidden minors provides a mechanism for studying critical configuration that lead to fractional solutions of associated linear programs. Some of these results are extended in [3] to p-nary (for p prime) group problems and in some case to arbitrary group problems. There, a sufficient condition is given for the Gomory cuts to define the convex hull of integer solutions of the group problem. This condition generalizes a known result for regular binary matroids where an alternative proof is given.

In practice, strong linear programming formulations are essential for solving hard problems. The paper [8] describes an integer programming decomposition approach and indicates its application to clustering problems, including graph partitioning. The approach involves column generation and a general framework for branching is given.

In [17] the Chvatal rounding procedure is extended to a procedure for generating all valid inequalities for mixed-integer 0-1 problems.

**D. Graph Theory**

Work in graph theory has focused on forbidden minor characterizations and their implications for optimization problems. In [6], the four problems considered are: Chinese postman, odd cut, max cut, and max odd circuit. These problems are all related to binary group problems over graphic or co-graphic matroids, and they constitute two blocking pairs of problems. A general framework for characterizing graphs with excluded minors by forbidden configura-

tion is presented and for each of the four cases such a characterization is given. This approach provides fast algorithms for the four problems and easy proofs of the max-flow, min-cut results for them. This work is carried further in [4], where graphs with no cube or dual cube (octahedron) are characterized by having a series-parallel reduction or a degree three node in a triangle. The latter configuration can be reduced giving an efficient means of recognizing such graphs.

**E. Parallel Computation** [18,19]

In the contexts of the set covering problem, we have done empirical studies of how branch-and-bound algorithms should be structured in a parallel computation environment. Important factors, such as the search and relaxation strategies, require different treatment, when many subproblems are processed simultaneously.

**F. Surveys and Books**

Reference [15], which is both a graduate text and reference on integer and combinatorial optimization received ORSA's 1989 Lanchester Prize for the outstanding publication of the year. References [5] and [16] are chapters of books on location and optimization, respectively.

**G. Human Resource Development**

Besides the Principal Investigators, Dr. Gabriele C. Sigismondi was supported half-time during most of the duration of the grant in a post-doctoral capacity. Four doctoral students have worked under the grant. Heesang Lee received his Ph.D. in March 1991 and is now on the research staff of Korea Telecommunications. Anuj Mehrotra, Pamela Vance, and Erick Wikum should receive doctoral degrees in 1992.

## II. Publications


1. R. Aboudi and G.L. Nemhauser, "Some Facets for an Assignment problem with Side Constraints," to appear in Operations Research, 1991.

2. R. Aboudi and G.L. Nemhauser, "An Assignment Problem with Side Constraints: Strong Cutting Planes and Separation," in Economic Decision Making: Games, Econometrics and Optimization, J. Gabszewicz, J.F. Richard and L.A. Wolsey (eds.), North-Holland, 1990.

3. S. Chopra, D.L. Jensen and E.L. Johnson, "Polyhedra of Regular p-nary Group Problems," Mathematical Programming, 43, 1-29, 1989.

4. S. Chopra and E.L. Johnson, "Octahedron Free and Cube Free Graphs," (Preprint, 1990).

5. G. Cornuejols, G.L. Nemhauser and L.A. Wolsey, "The Uncapacitated Facility Location Problem," in Discrete Location Theory, R.L. Francis and P. Mirchandini, (eds.), Wiley, 119-172 (1990).

6. H. Gan and E.L. Johnson, "Four Problems on Graphs with Excluded Minors," Mathematical Programming, 45, 311-330, 1989.

7. E.L. Johnson, "On Binary Group Problems Having the Fulkerson Property," in Combinatorial Optimization, B. Simeone (ed.), Springer-Verlag, 57-112, 1989.

8. E.L. Johnson, " Modeling and Strong Linear Programs for Mixed Integer Programming," in Algorithms and Model Formulation in

Mathematical Programming, NATO ASI Vol. 51, S. Wallace (ed.), Springer-Verlag, pp. 3-43, 1989.

9. H. Lee, "A Polyhedral Approach to Maximizing Submodular Functions," Ph.D. Dissertation, Georgia Institute of Technology, March, 1991.

10. G.L. Nemhauser and S. Park "A Polyhedral Approach to Edge Coloring," ISyE No. J-89-01, to appear in Operations Research Letters, 1991.

11. G.L. Nemhauser and M. Savelsbergh, "A Cutting Plane Algorithm for the Single Machine Scheduling Problem with Release Times," ISyE No. J-91-05 in Proceedings of NATO Advanced Study Institute: "New Frontiers in Theory & Practice of Combinatorial Optimization", Springer, 1991.

12. G.L. Nemhauser, M. Savelsbergh and G. Sigismondi, "MINTO: A Mixed INTeger Optimizer," in preparation.

13. G.L. Nemhauser and G. Sigismondi, "A Strong Cutting Plane/ Branch-and-Bound Algorithm for Node Packing," ISyE Report No. J-89-03, to appear in Operational Research.

14. G.L. Nemhauser, G. Sigismondi, and P. Vance, "A Characterization of the Coefficients in Facet-Defining Lifted Cover Inequalities," ISyE Report No. J-89-06 (submitted for publication).

15. G.L. Nemhauser and L.A. Wolsey, Integer and Combinatorial Optimization, Wiley, 1988.

16. G.L. Nemhauser and L.A. Wolsey, "Integer Programming," in Handbooks in Operations Research and Management Science, Vol. 1, Optimization, G.L. Nemhauser, A.H.G. Rinnooy Kan and M.J. Todd, eds., pp.447-528, North-Holland, 1991.

17. G.L. Nemhauser and L.A. Wolsey, "A Recursive Procedure for Generating all Cuts for Mixed-Integer Programs," Mathematical Programming 46, 379-390, (1990).

18. R. Rushmeier and G.L. Nemhauser, "Performance of Parallel Branch-and-Bound Algorithms for the Set Covering Problem," ISyE Report No. J-89-02 (submitted for publication).

19. R. Rushmeier and G.L. Nemhauser, "Performance of a Parallel Cost Splitting Algorithm for the Set Covering Problem," ISyE Report No. J-90-03 (submitted for publication).

MB Number 345-0058

ATIONAL SCIENCE FOUNDATION
800 G STREET, NW
/ASHINGTON, DC 20550



PI/PD Name and Address

George L. Nemhauser
Department of Industrial and Systems
GA Tech Res Corp - GTRI
Engineering
Atlanta GA 30332

# NATIONAL SCIENCE FOUNDATION
# FINAL PROJECT REPORT

## PART I - PROJECT IDENTIFICATION INFORMATION

1. Program Official/Org. Dr. Hank Grant - DDM

2. Program Name OPERATIONS RESEARCH & PRODUCTION SYSTEMS

3. Award Dates (MM/YY) From: 06/86 To: 05/92

4. Institution and Address
GA Tech Res Corp - GTRI
Atlanta GA 30332

5. Award Number 8719128

6. Project Title
Research In Mixed-Integer Programming

This Packet Contains
NSF Form 98A
And 1 Return Envelope

SF Grant Conditions (Article 17, GC-1, and Article 9, FDP-II) require submission of a Final Project eport (NSF Form 98A) to the NSF program officer no later than 90 days after the expiration of the ward. Final Project Reports for expired awards must be received before new awards can be made ISF Grant Policy Manual Section 677).

low, or on a separate page attached to this form, provide a summary of the completed project and technical information. Be re to include your name and award number on each separate page. See below for more instructions.

## PART II - SUMMARY OF COMPLETED PROJECT (for public use)

ne summary (about 200 words) must be self-contained and intelligible to a scientifically literate reader. Without restating the roject title, it should begin with a topic sentence stating the project's major thesis. The summary should include, if pertinent the project being described, the following items:

- The primary objectives and scope of the project
- The techniques or approaches used only to the degree necessary for comprehension
- The findings and implications stated as concisely and informatively as possible

## PART III - TECHNICAL INFORMATION (for program management use)

List references to publications resulting from this award and briefly describe primary data, samples, physical collections, inventions, software, etc. created or gathered in the course of the research and, if appropriate, how they are being made available to the research community. Provide the NSF Invention Disclosure number for any invention.

| | |
|---|---|
| Principal Investigator/Project Director Signature | Date |

**IMPORTANT:**
**MAILING INSTRUCTIONS**
**Return this *entire* packet plus all attachments in the envelope attached to the back of this form. Please copy the information from Part I, Block I to the *Attention block* on the envelope.**

GEORGE L. NEMHAUSER
AWARD NO. 8719128

## PART II. SUMMARY OF COMPLETED PROJECT

This project developed algorithms and prototype software for solving large-scale mixed-integer programs (MIPs) that arise in logistics, production scheduling and resource allocation. A MIP is a linear optimization model in which some of the variables are required to be equal to 0 or 1. The work is motivated by the tremendous demand for efficient and robust MIP software for solving problems in these domains.

The most significant result is the modular, experimental software system called **MINTO** (Mixed-Integer Optimizer). MINTO allows a researcher to customize a general mixed-integer optimization code through application routines and thereby concentrate on problem specific aspects rather than the data structures and implementation details of, for instance, linear programming and branch-and-bound algorithms.

MINTO's driver is a linear programming based branch-and-bound algorithm. The design of MINTO is based on the philosophy that to solve MIPs efficiently one needs to take advantage of the problem structure. Therefore, MINTO provides entry points that allow an application program to enter problem specific knowledge that can be used to generate, for example, primal solutions, strong cutting planes and special branching rules.

We have developed application programs for some generic problems. These include distribution, job shop scheduling, clustering, node packing and submodular function maximization. We believe that MINTO will be widely used by researchers working in both methodology and applications of MIP, and we have begun to distribute the software at a nominal cost to cover our maintenance. The response has been substantial.

GEORGE L. NEMHAUSER - AWARD NO. 8719128

## III. TECHNICAL INFORMATION


1. R. Aboudi and G.L. Nemhauser, "Some Facets for an Assignment problem with Side Constraints," Operations Research 39, 244-250,1991.

2. R. Aboudi and G.L. Nemhauser, "An Assignment Problem with Side Constraints: Strong Cutting Planes and Separation," in Economic Decision Making: Games, Econometrics and Optimization, J. Gabszewicz, J.F. Richard and L.A. Wolsey (eds.), North-Holland, 1990.

3. C. Barnhart, E.L. Johnson, G.L. Nemhauser, G. Sigismondi and P. Vance, "Solving a Large-Scale Distribution Problem: A real Example of Using a Good Formulation to Solve a Mixed-Integer Program," COC working paper, No. 92-02, 1992

4. S. Chopra, D.L. Jensen and E.L. Johnson, "Polyhedra of Regular p-nary Group Problems," Mathematical Programming, 43, 1-29, 1989.

5. S. Chopra and E.L. Johnson, "Octahedron Free and Cube Free Graphs," 1990.

6. G. Cornuejols, G.L. Nemhauser and L.A. Wolsey, "The Uncapacitated Facility Location Problem," in Discrete Location Theory, R.L. Francis and P. Mirchandini, (eds.), Wiley, 1990.

7. H. Gan and E.L. Johnson, "Four Problems on Graphs with Excluded Minors," Mathematical Programming, 45, 311-330, 1989.

8. E.L. Johnson, "On Binary Group Problems Having the Fulkerson Property," in Combinatorial Optimization, B. Simeone (ed.), Springer-Verlag, 57-112, 1989.

9. E.L. Johnson, " Modeling and Strong Linear Programs for Mixed Integer Programming," in Algorithms and Model Formulation in Mathematical Programming, NATO ASI Vol. 51, S. Wallace (ed.), Springer-Verlag, pp. 3-43, 1989.

10. E.L. Johnson and G.L. Nemhauser, "Recent Developments and Future Directions in Mathematical Programming," IBM Systems Journal 31, pp. 79-93, 1992.

11. H. Lee, "A Polyhedral Approach to Maximizing Submodular Functions," Ph.D. Dissertation, Georgia Institute of Technology, 1991.

12. G.L. Nemhauser and S. Park "A Polyhedral Approach to Edge Coloring," Operations Research Letters 10, 315-322, 1991.

**III. TECHINICAL INFORMATION** (cont'd)

13. G.L. Nemhauser and M. Savelsbergh, "A Cutting Plane Algorithm for the Single Machine Scheduling Problem with Release Times," in Proceedings of NATO Advanced Study Institute: "New Frontiers in Theory & Practice of Combinatorial Optimization", Springer, 1991.

14. G.L. Nemhauser, M. Savelsbergh and G. Sigismondi, "MINTO: A Mixed INTeger Optimizer," COC working paper, No. 91-03A.

15. G.L. Nemhauser and G. Sigismondi, "A Strong Cutting Plane/ Branch-and-Bound Algorithm for Node Packing," ISyE Report No. J-89-03, in Journal of the Operations Research Society 43, 443-457, 1992.

16. G.L. Nemhauser, G. Sigismondi, and P. Vance, "A Characterization of the Coefficients in Facet-Defining Lifted Cover Inequalities," ISyE Report No. J-89-06, 1989.

17. G.L. Nemhauser and L.A. Wolsey, Integer and Combinatorial Optimization, Wiley, 1988.

18. G.L. Nemhauser and L.A. Wolsey, "Integer Programming," in Handbooks in Operations Research and Management Science, Vol. 1, Optimization, G.L. Nemhauser, A.H.G. Rinnooy Kan and M.J. Todd, eds., pp. 447-528, North-Holland, 1991.

19. G.L. Nemhauser and L.A. Wolsey, "A Recursive Procedure for Generating all Cuts for Mixed-Integer Programs," Mathematical Programming 46, pp.379-390, 1990.

20. R. Rushmeier and G.L. Nemhauser, "Performance of Parallel Branch-and-Bound Algorithms for the Set Covering Problem," ISyE Report No. J-89-02, 1989.

21. R. Rushmeier and G.L. Nemhauser, "Performance of a Parallel Cost Splitting Algorithm for the Set Covering Problem," ISyE Report No. J-90-03, 1990.

**Software**

MINTO: "A Mixed INTeger Optimizer" is available on request for a nominal distribution and maintenance fee.

## PART IV — FINAL PROJECT REPORT — SUMMARY DATA ON PROJECT PERSONNEL

**(To be submitted to cognizant Program Officer upon completion of project)**

The data requested below are important for the development of a statistical profile on the personnel supported by Federal grants. The information on this part is solicited in response to Public Law 99-383 and 42 USC 1885C. All information provided will be treated as confidential and will be safeguarded in accordance with the provisions of the Privacy Act of 1974. You should submit a single copy of this part with each final project report. However, submission of the requested information is not mandatory and is not a precondition of future award(s). Check the "Decline to Provide Information" box below if you do not wish to provide the information.

Please enter the numbers of individuals supported under this grant.
Do not enter information for individuals working less than 40 hours in any calendar year.

| | Senior Staff | | Post-Doctorals | | Graduate Students | | Under-Graduates | | Other Participants[1] | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Male | Fem. | Male | Fem. | Male | Fem. | Male | Fem. | Male | Fem. |
| **A. Total, U.S. Citizens** | 2 | | 0 | | | 1 | | | | |
| **B. Total, Permanent Residents** | 0 | | 1 | | | 1 | | | | |
| U.S. Citizens or Permanent Residents[2]: | | | | | | | | | | |
| American Indian or Alaskan Native ... | | | | | | | | | | |
| Asian ... | | | | | | 1 | | | | |
| Black, Not of Hispanic Origin ... | | | | | | | | | | |
| Hispanic ... | | | 1 | | | | | | | |
| Pacific Islander ... | | | | | | | | | | |
| White, Not of Hispanic Origin ... | 2 | | | | | 1 | | | | |
| **C. Total, Other Non-U.S. Citizens** | 0 | | 1 | | | 1 | | | | |
| Specify Country 1. Netherlands | | | 1 | | | | | | | |
| 2. Korea | | | | | | 1 | | | | |
| 3. | | | | | | | | | | |
| **D. Total, All participants (A + B + C)** | 2 | | 2 | | | 3 | | | | |
| **Disabled[3]** | | | | | | | | | | |

☐ Decline to Provide Information: Check box if you do not wish to provide this information (you are still required to return this page along with Parts I-III).

[1]Category includes, for example, college and precollege teachers, conference and workshop participants.

[2]Use the category that best describes the ethnic/racial status for all U.S. Citizens and Non-citizens with Permanent Residency. *(If more than one category applies, use the one category that most closely reflects the person's recognition in the community.)*

[3]A person having a physical or mental impairment that substantially limits one or more major life activities; who has a record of such impairment; or who is regarded as having such impairment. *(Disabled individuals also should be counted under the appropriate ethnic/racial group unless they are classified as "Other Non-U.S. Citizens.")*

**AMERICAN INDIAN OR ALASKAN NATIVE:** A person having origins in any of the original peoples of North America, and who maintain cultural identification through tribal affiliation or community recognition.

**ASIAN:** A person having origins in any of the original peoples of East Asia, Southeast Asia and the Indian subcontinent. This area includes, for example, China, India, Indonesia, Japan, Korea and Vietnam.

**BLACK, NOT OF HISPANIC ORIGIN:** A person having origins in any of the black racial groups of Africa.

**HISPANIC:** A person of Mexican, Puerto Rican, Cuban, Central or South American or other Spanish culture or origin, regardless of race.

**PACIFIC ISLANDER:** A person having origins in any of the original peoples of Hawaii; the U.S. Pacific Territories of Guam, American Samoa, or the Northern Marianas; the U.S. Trust Territory of Palau; the Islands of Micronesia or Melanesia; or the Philippines.

**WHITE, NOT OF HISPANIC ORIGIN:** A person having origins in any of the original peoples of Europe, North Africa, or the Middle East.